# SPATIAL VARIATION OF TIDAL AND GRAVITAIONAL CIRCULATION EXCHANGES IN THE RED RIVER ESTUARY

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## 1. INTRODUCTION

The net flow of water into and out of estuaries influences the exchanges with the surrounding coastal region. It plays a vital role in the control the estuarine environment by regulating the transports of salinity, nutrients, sediments, and pollutants. In this study, we proposed a flushing rate method to investigate the estuarine hydrodynamic processes such as the tidal exchange and gravitational circulation exchange. The study area is the Red River estuary (RRE) near the southwest part of the Gulf of Tonkin in Vietnam (Fig. 1).

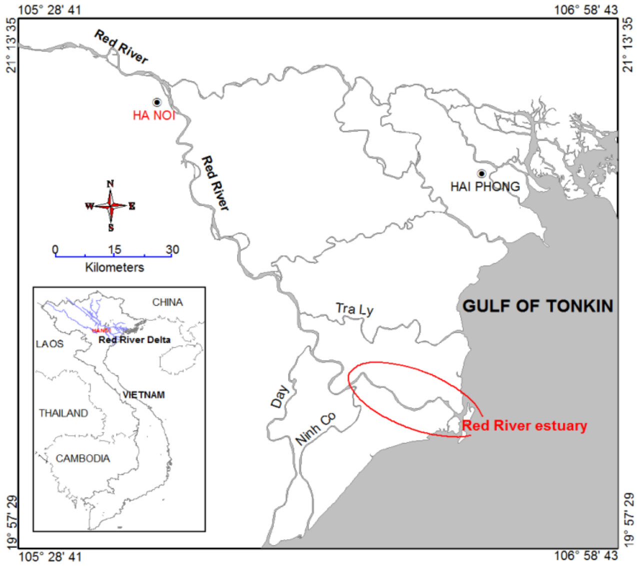


**Fig. 1** The various distributaries of the Red River Delta in the North of Vietnam (inset). The oval indicates the RRE.

## 2. METHODS

The flushing rate (*F*) is defined as the rate at which water in a water body is replaced by other water (Shaha et al., 2010). Officer and Kester (1991) have applied the flushing rate to investigate the transport process in the Narragansett bay. They calculated a single flushing rate for the entire system based on the average salinity in the bay. However, according to Monsen et al. (2002), the single flushing rate for a system is not valid for temporal and spatial situations. As the single flushing rate does not prove to be meaningful in predicting the spatial variation of the transport process, we split the RRE into multiple segments and calculated the flushing rate value for each segment. The spatial variations of gravitational circulation and tidal exchanges were examined after all flushing-rate values were determined.
For a multi-segment estuary, the salt balance equation at a steady state condition is:

$$QS - AD\frac{\partial S}{\partial x} = 0 \qquad (1)$$

where $Q$ represents the river discharge associated with residual flow, $S$ is the salinity, $A$ is the tidal average cross-sectional area, and $D$ is the dispersion coefficient.
The flushing rate $F$ is then given:

$$F_i = \frac{QS_0}{S_0 - S_i} \qquad \text{where } F = AD/\Delta x \qquad (2)$$

where the subscript $i$ indicates the segment of interest, $S_0$ and $S_i$ are the salinity at the downstream end and upstream end of the segment $i$, respectively. The transport of salt is defined by a sum of the gravitational circulation flux ($F_G$) and tide-driven diffusive flux ($F_T$). The quantity $F$ represents the combined tide-driven and gravitational circulation exchanges. The total salt flux is given by $F = F_G + F_T$. For a specific river discharge, the tide-driven exchange is superior to the gravitational circulation exchange if $F_T > F_G$, while the gravitational circulation exchange exceeds the tide-driven exchange if $F_T < F_G$. Shaha et al. (2010) determined the intercept value of the density-driven salt flux $F_{Ginc}$ ($F_{Ginc}$ = Q), indicating a dominance of the gravitational circulation exchange if $F - F_{Ginc} < Q$.

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Because the RRE is well mixed during the dry season (IHME, 2009), the flushing rate may be calculated using Eq. (2) considering the estuary system as a single layer with multiple segments. The RRE was divided into 12 segments, at intervals of 4 km. This segmentation provides a box model approximation of the longitudinal salinity gradient. The flushing rate was calculated among multiple segments for the daily average freshwater discharge.

The datasets used in this investigation are salinity and river discharge. A series of field measurements of salinity was conducted during the dry season in 2008 by the Institute of Meteorology, Hydrology, and Environment. The longitudinal transects for salinity were carried out at high water and low water during a spring tide on December 15, 2008. The daily river discharge in the RRE is about 170 $m^3/s$.

## 3. RESULTS

The flushing rate was calculated for 12 segments starting from the twelfth segment in the upstream end to the first segment adjacent the sea. Fig. 2 illustrates the calculation result of flushing rate for the RRE at high water and low water during a spring tide. At the high water, the flushing rate increases from 170 $m^3/s$ at the upstream end to 3339 $m^3/s$ at the river mouth. At the low water, the flushing rate remains constant value of 170 $m^3/s$ from the segment 12 to 7. It then starts increasing from the segment 7 toward the mouth. The flushing rate varies significantly between high water and low water landward of 8 km from the river mouth of the RRE. The flushing rate at the high water is approximately six times greater than that at low water. The higher the flushing rate, the more the salt flux is.

It appears that the total salt flux ($F$) at the high water is much greater than the intercept value of the gravitational circulation flux ($F_{Ginc}$), suggesting a dominant driving process of the tidal dispersive flux along the RRE. In contrast, the tidal exchange is dominant over the longitudinal circulation exchange within a distance landward of 8 km from the river mouth at the low water. The combined contribution of tidal exchange and gravitational circulation exchange is only found from the segment 4 to 5 at low water. This is attribute to the weaker turbulence at the low water that accelerates the gravitational circulation exchange and reduces the influence of the tide. The gravitational circulation exchange is superior to the tidal exchange if $F$ - $F_{Ginc}$ < Q (Shaha et al., 2010). Computed results indicate that the gravitational circulation exchange is entirely dominant the salt transport process from the segment 6 to 12 at the low water.

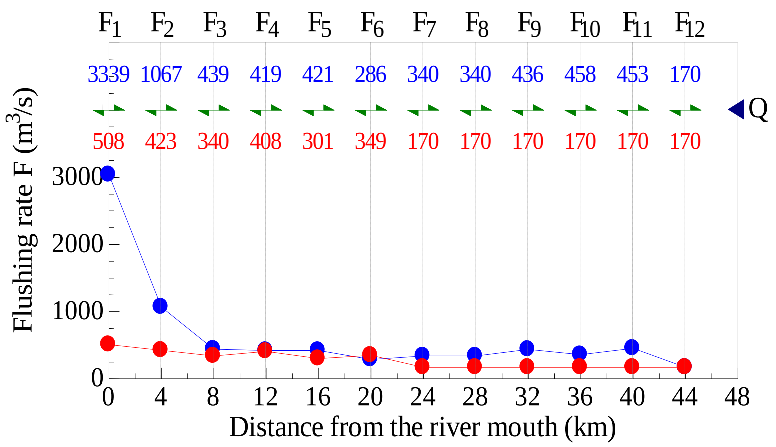


**Fig. 2** Spatial variation of the flushing rate ($m^3/s$) at high water and low water.

## 4. CONCLUSION

To investigate spatial variation of the gravitational circulation and tide driven exchanges in the RRE, the flushing rate method was applied for multiple segments using longitudinal transects of measured salinity. We found that the tide-driven dispersion dominates the salt transport process in the entire system at the high water. However, as the tidal forcing decreases at the low water, both gravitational circulation and tidal exchanges are spatially varied. The tidal exchange is dominant the salt flux in the outer zone near the river mouth. The combined contribution of two fluxes is modulated in the central and inner zones. Results suggested the use of spatially varying flushing rate to estimate the tide-driven and gravitational circulation exchanges. It may help to understand the distribution of dissolved concentrations in an estuary.

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